High critical current densities in ultrathin $YBa_2Cu_3O_{7-\delta}$ films sandwiched between $(Pr_xY_{1-x})Ba_2Cu_3O_{7-\delta}$ layers

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$YBa_2Cu_3O_{7-\delta}$ (YBCO) films with nominal thicknesses of 1–4 unit cells were grown by pulsed laser deposition using $(Pr_xY_{1-x})Ba_2Cu_3O_{7-\delta}$ [(Pr_xY_{1-x})BCO] ($1 \geqslant x \geqslant 0$) as buffer layers and cap layers. The films of 1 unit cell thick were superconducting for all the x values while T_c increased when x was reduced. For adjacent layers of $(Pr_{0.6}Y_{0.4})$BCO which is semiconducting, a T_c of 43 K and J_c of 2×10^6 A/cm^2 for $B \parallel ab$ and 4×10^5 A/cm^2 for $B\perp ab$ at $B=7$ T and 4.2 K were obtained in a one-unit cell thick YBCO layer. The J_c values of a few unit cell thick YBCO layers nearly approached that of thick YBCO films. The results suggest the absence of significant weak-link effects in these films.

The CuO_2 planes in cuprate superconductors are considered to be responsible for the mobile carriers and the high transition temperature T_c. What are the intrinsic properties of a single-unit cell sheet of such materials is therefore a fundamentally significant question. Furthermore, high quality ultrathin $YBa_2Cu_3O_{7-\delta}$(YBCO) films are also required for device applications.[1] There have been many studies on YBCO single-unit cell layers, but the results to date are not consistent.[2-9] Experiments on superlattices of 1.2 nm YBCO with thick $PrBa_2Cu_3O_{7-\delta}$ (PrBCO) layers indicate that 1-unit cell thick YBCO layer is superconducting.[3,4] Terashima *et al.*[6] and Cieplak *et al.*[7] have observed that a single one-unit cell thick layer of YBCO in a trilayer structure with PrBCO buffer and cap layers is superconducting. However, contrary results have also been reported on the same sample structure.[8,9] Chan *et al.*[8] indicated that the results could be heavily influenced by interdiffusion and surface roughness. On the other hand, severely reduced J_c was reported in superlattices of 1-cell thick YBCO with thick PrBCO layers, which has been attributed to the weak links formed at the unit cell steps in YBCO layers observed from cross sectional transmission electron microscopy.[10] In this letter, we present a study on the superconducting properties of ultrathin YBCO layers in a trilayer structure using (Pr_xY_{1-x})BCO ($1 \geqslant x \geqslant 0$) as buffer and cap layers.

An atomically flat and well-lattice-matched substrate is essential for growing high quality ultrathin films. We investigated the surface morphology of (100) $SrTiO_3$ (STO) and (110) $NdGaO_3$ (NGO) substrates using atomic force microscopy (AFM, Nanoscope III, Digital Instruments). The lattice mismatch between the a- and b-axis of YBCO and the substrates is about 0.7% and −0.7% for (110)NGO and 2% and 0.3% for (100)STO, respectively. The AFM images of (100)STO show atomically flat background surface, with root mean square (rms) surface roughness being 0.19 nm, but outgrowth-like features exist with peak to valley (PV) heights of 1–2 nm. The atomically flat surface is also observed for unannealed (110)NGO surface, showing an rms surface roughness of ~0.2 nm. Figure 1 shows an AFM image of a NGO substrate after annealing in oxygen for about an hour at 950 °C. Smooth surfaces were found with an rms surface roughness of 0.12 nm. As seen in the line scan, there is a periodic feature with PV height of about 0.4 nm over a distance of ~300 nm across the substrate, which corre-

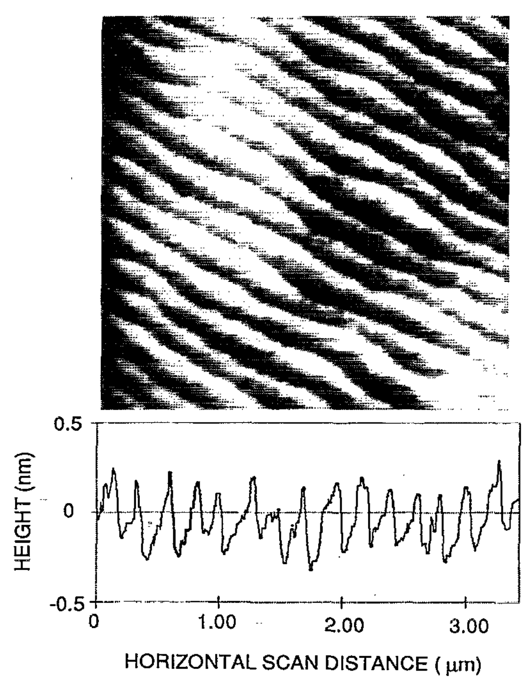

FIG. 1. AFM images (upper) of $NdGaO_3$ (110) substrate surface after annealing in O_2. Line scan profile (lower), showing a peak to valley surface roughness height of about 0.4 nm and ~300 nm average horizontal separation of each strand.

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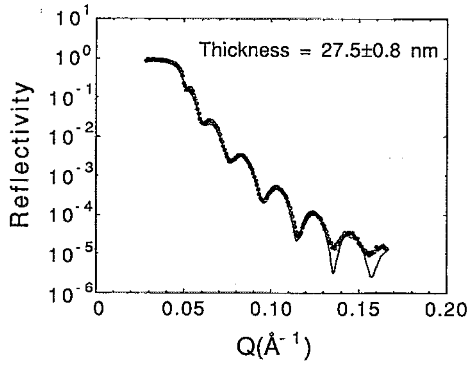

FIG. 2. Low angle x-ray diffraction scan of a nominal 27.6 nm YBCO on (110)NGO where $Q=(4\pi/\lambda)\sin\ \theta$ with $\lambda=1.5418$ Å. The solid line is a fitting curve using thickness of (27.5 ± 0.8) nm.

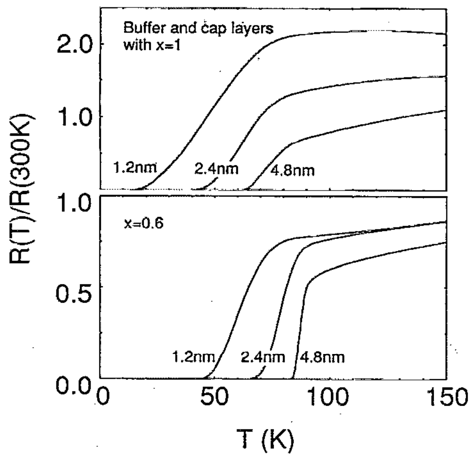

FIG. 3. Resistive transition curves for 1-, 2-, and 4-unit cell thick YBCO with (a) $x=1$, (b) $x=0.6$ for the adjacent layers of (Pr_xY_{1-x}) BCO.

sponds to the unit cell height of NGO, indicating a slight miscut ($\sim 0.15°$) of the substrate.

The samples were made by pulsed-laser deposition. Computer-controlled laser triggering and target exchange were used to sequentially deposit YBCO and (Pr_xY_{1-x})BCO *in situ*. The ultrathin YBCO layers were grown on 6-unit-cell (7.2 nm) (Pr_xY_{1-x})BCO buffer layers and then covered by $\sim$20 nm (Pr_xY_{1-x})BCO layers to protect the surface of YBCO from degradation. X-ray diffraction showed a *c*-axis orientation for all the layers. Both NGO and STO have been used as substrate, and higher T_c values were constantly observed for the films on (110)NGO than those of the same thickness on (100) STO. It has been reported by *in situ* RHEED measurements[5,9] that high quality layer by layer grown YBCO film can be achieved only when the STO substrate is ion milled and then *in situ* annealed or a STO thin film is first deposited prior to thin-film deposition. The substrate was held at 730 °C in 100 mTorr oxygen during deposition. The laser energy density was 1.7 J/cm^2 and the deposition rate was $\sim$0.02 nm/pulse with a repetition rate of 1 Hz. After deposition, the samples were cooled to room temperature in 200 Torr oxygen.

Special efforts were made to control the film thickness accurately. Films of $\sim$30 nm YBCO were deposited and their thicknesses were measured with a profilometer to give the deposition rate for each laser shot. The deposition-rate calibrations were made right before and immediately after the ultrathin-film deposition to ensure the consistency of the calibration. The thickness of the ultrathin films was then determined by the number of laser pulses. The thickness of some samples was also cross-calibrated using low angle x-ray diffraction, as shown in Fig. 2 for a nominal 27.6 nm thick YBCO film. The solid line is the calculated curve of the intensity fringes caused by the interference between the surface and interface of the film.[11,12] The thickness value obtained from the fitting is 27.5 ± 0.8 nm which is consistent with that determined by the number of laser pulses. Zheng *et al.*[13] reported that YBCO deposited on STO substrate grows in the Stranski–Krastanov mode with layer-by-layer growth up to 8–16 unit cells. We also did not observe screw dislocations in a 7.2 nm film from the AFM images.

The sample was patterned into a standard four-probe bridge by laser patterning for transport measurements. Figure 3 shows the resistive transition curves of 1-, 2-, and 4-unit cell thick YBCO layers with $x=1$ and $x=0.6$ for the adjacent (Pr_xY_{1-x})BCO layers. For $1\geqslant x\geqslant 0.5$, (Pr_xY_{1-x})BCO is a semiconductor and its resistivity increases rapidly with increasing x.[14] Since the thickness of the YBCO layers is so small, the temperature-dependence of the resistance shown in the figure has substantial contribution from the adjacent (Pr_xY_{1-x})BCO layers. If we subtract the resistance of the adjacent layers inferred from the resistivity of a 30 nm thick (Pr_xY_{1-x})BCO layer made under identical conditions, the temperature dependence of the resistance of the unit-cell thick YBCO films shows metallic behavior in all the cases. As seen in the figure, the 1-unit cell thick YBCO layer is superconducting for both x values and a zero-resistance T_c of 43 K was obtained for $x=0.6$. The T_c's measured by ac susceptibility are consistent with those from the resistance measurements. Samples with x values in (Pr_xY_{1-x})BCO ranging from 0 to 1 have been made and the T_c of the one-unit cell thick YBCO layer increases almost linearly with decreasing x. Detailed study on the effects of adjacent layers on the superconductivity of the unit cells thick YBCO layers will be published elsewhere. We have made more than 20 samples with one-unit cell thick YBCO layer, and reproducible results were obtained.

The critical current density, J_c, was measured as a function of temperature and magnetic field up to 7 T. A voltage criterion of 1 μV/mm was used to define the critical current. Figure 4 shows J_c versus temperature curves for YBCO layers of 1, 2, 3, and 4 unit cells in thicknesses. J_c values as high as 2×10^6, 6×10^6, 1.2×10^7 and 1.5×10^7 A/cm^2 at 4.2 K and zero field were obtained for 1-,2-,3-, and 4-unit cell thick YBCO layers respectively. The J_c of the 1 unit cell thick film is only one order of magnitude smaller than the best thick-film value (5×10^7 A/cm^2), and the values of the 3- and 4-unit cell thick films are

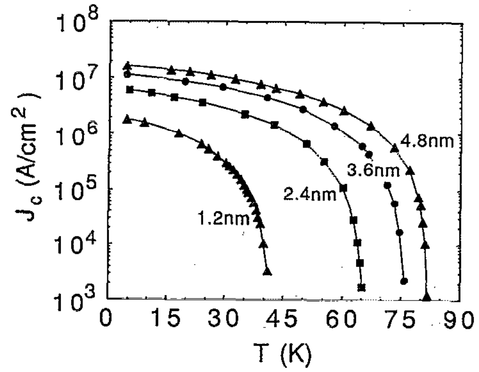

FIG. 4. Temperature dependence of critical current for 1, 2, 3, and 4-unit cell thick YBCO with $(Pr_{0.6}Y_{0.4})BCO$ adjacent layers at zero magnetic field.

already very close to it. The temperature dependence of J_c is very similar to that of the bulk samples and $J_c(T)/J_c(0)$ vs T/T_c curves for all the samples collapse into one curve. In Fig. 5, the magnetic-field dependence of J_c for the field parallel and perpendicular to the *ab* plane are shown for a 1 unit cell YBCO layer along with a 200 nm film measured at 4.2 K.[15] A very weak dependence of J_c on magnetic field was found for the field parallel to *ab* plane, which is expected from the two-dimensional model. Surprisingly, for the field perpendicular to the *ab* plane, the suppression of J_c was also weak and a value of 4×10^5 A/cm^2 for 1 unit cell thick YBCO was obtained even at 7 T. As seen in the figure, the J_c suppression for both 1 unit cell and thick film is similar. These results indicate that the critical current densities in our 1 unit cell YBCO layer is not dominated by weak links as proposed by Pennycook *et al.* for superlattices with the same YBCO layer thicknesses.[10] The high J_c values are not due to the surface or interface pinning, which may differ from the thick film, since J_c for $B\perp$ *ab* of all the samples show a magnetic-field dependence similar to that of thick YBCO films at low temperature and the J_c

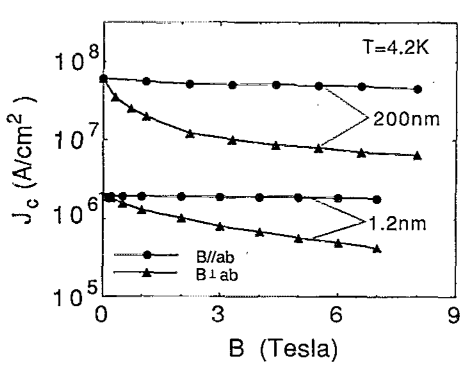

FIG. 5. J_c vs B for 1-unit cell thick YBCO with $(Pr_{0.6}Y_{0.4})BCO$ adjacent layers at 4.2 K. The result of ~200 nm YBCO at 4.2 K is shown for comparison (Ref. 15).

of 4 unit cell thick YBCO is already close to the thick film value. The results also confirm the theoretical estimation that high density pinning centers are present in each unit cell layer in YBCO films.[16] The results also tends to suggest very good connectivity of these 1 unit cell layers, which is consistent with a Stranski–Krastanov growth mode as proposed by Zheng *et al.*[13]

In summary, we have observed superconductivity for nominally 1-unit cell thick YBCO layer with $(Pr_xY_{1-x})BCO$ as adjacent layers for the whole range of x values, and the results are reproducible. High T_c of 43 K was obtained for the 1-unit cell thick YBCO layer with $x=0.6$ in the adjacent layers. Critical current densities of 2×10^6 A/cm^2 for $B\|$ *ab* and 4×10^5 A/cm^2 for $B\perp$ *ab* in 7 T were obtained at 4.2 K for the same sample. This suggests that a high density of pinning centers is present in each unit cell YBCO layer and the result is not dominated by the weak links. The J_c of YBCO layers of only a few unit cell thick already approaches the thick-film value. The results also have promising implications of high current capacity of very thin films, which is required for certain devices.

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